Status of the Advanced Locomotive Propulsion System (ALPS) Project

J.D. Herbst, R.F. Thelen, and W.A. Walls
The University of Texas at Austin
Center for Electromechanics

Abstract

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently developing an Advanced Locomotive Propulsion System (ALPS) as part of the Next Generation High Speed Rail program sponsored by the Federal Railroad Administration (FRA). Testing of the advanced propulsion system will be conducted as a portion of the FRA Non-Electric High Speed Locomotive Demonstration program. The project goal is to develop a non-electric locomotive propulsion system capable of 150 mph operation on existing infrastructure with good fuel economy and low noise and pollutant emissions. The propulsion system consists of two major elements: (1) a high speed generator directly coupled to a 5,000 hp gas turbine (turboalternator) to provide prime power and (2) an energy storage flywheel to provide additional power for acceleration and speed maintenance on grades, and to recover kinetic energy during braking. In addition to improving the overall system efficiency, the energy storage flywheel also provides load leveling for the turbine, reducing thermal cycling and significantly extending turbine maintenance intervals.

The paper provides an overview of the ALPS system and presents the results of performance simulations to illustrate the benefits of the system. The paper also provides the current status of the project, along with component test results as available.

KEYWORDS: *flywheel energy storage, turbine-electric locomotive*

Introduction

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently leading a team of uniquely qualified members in the development of an Advanced Locomotive Propulsion System (ALPS) as part of the Next Generation High Speed Rail program sponsored by the Federal Railroad Administration (FRA). Table 1 shows the ALPS team members and their areas of responsibility.

The goal of the project is to develop a non-electric locomotive propulsion system capable of 150 mph operation on existing infrastructure with good fuel economy and low noise and pollutant emissions. The development of 150 mph capable, non-electric trainsets which can operate on existing track infrastructure requires lighter locomotives with greater horsepower than existing diesel-electric locomotives. To achieve this goal, the ALPS propulsion system incorporates two major elements: (1) a high speed generator directly coupled to a 5,000 hp gas turbine (turboalternator) to provide prime power and (2) a flywheel energy storage system to provide additional power for acceleration and speed maintenance on grades, and to recover kinetic energy during locomotive dynamic braking. In addition to improving the overall system efficiency, the flywheel also provides load leveling for the turbine, resulting in reduced thermal cycling and significantly extending turbine maintenance intervals.

Table 1. ALPS project team members

ALPS Team Member	Area of Responsibility
Center for Electromechanics	flywheel/alternator development project management
Honeywell International	alternator development turbine manufacturing
AAR/TTCI*	equipment testing train Performance modeling
Seneca Group	market assessment performance requirements
Argonne National Laboratory	system safety analysis flywheel containment

*Association of American Railroads Transportation Technology Center, Inc.

Testing of the advanced propulsion system will be conducted in conjunction with the locomotive currently under development by Bombardier Transportation under the FRA High Speed Non-Electric Passenger Locomotive Demonstration Program. After completion of the Bombardier baseline system testing, the ALPS turboalternator package will be integrated into the Bombardier locomotive for a rolling demonstration of the advanced propulsion system. Size constraints imposed by the use of the Bombardier locomotive for the ALPS system demonstration will require the prototype flywheel energy storage system to be integrated into a tender car for the initial demonstrations. For a production propulsion system, it is envisioned that the flywheel energy storage system will be integrated into the locomotive chassis.

System Description

Fig. 1 shows the basic ALPS power flow schematic. During normal operation, the ALPS system works much like a conventional diesel electric locomotive, with ac power from the turbine driven generator rectified and supplied to the dc bus. A bidirectional power converter connected to the dc bus then provides variable frequency ac to the traction motors, in response to the locomotive speed and torque requirements. For higher power operation, additional power can be provided to the dc bus from the flywheel energy storage system. In this mode, a second bidirectional power converter connected to the flywheel will rectify the output of the flywheel driven motor/generator and feed it into the dc bus, supplementing the power from the turboalternator.

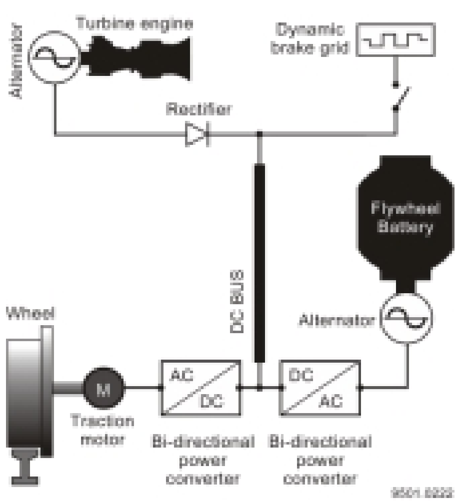

Fig. 1. ALPS power flow diagram

The current flywheel energy storage system design will provide an additional 3,000 hp to the traction system for approximately three minutes.

During dynamic braking operation, power from the traction motors can be dissipated in conventional dynamic brake resistor grids or it can be used to replenish the flywheel energy store, depending on the current status and future power requirements of the system. In flywheel replenishment mode, the traction motors feed power to the dc bus through the traction inverters, and the high frequency bidirectional power converter then provides variable frequency ac to drive the flywheel motor/generator as a high speed motor. Once the flywheel energy store is replenished, the remaining braking energy can be dissipated in the dynamic brake resistor grids. Additional braking power can always be provided by the existing pneumatic brake system on the train.

The ALPS system controller will have two basic classes of actions, depending on the required response time. For fast transient events such as loss of load due to a wheel slip event, the controller can divert power from the traction motors to the dynamic brake resistor grids to maintain a load on the high speed generator and prevent turbine or generator overspeeds. The response time for this type of event is on the order of milliseconds. For slower transients (on the order of seconds), the propulsion system controller will be optimized to minimize changes to the turboalternator power setting. Minimizing changes in turboalternator power will reduce the number of thermal cycles experienced by the turbine, which can significantly extend turbine maintenance intervals.

For example, if the traction power demand increases due to an increase in grade, the additional power can be supplied by the flywheel without increasing the turboalternator power output. Conversely, if traction power demand decreases due to a down grade or speed reduction for a curve, a portion of the turboalternator power can be supplied to the flywheel, reducing the power input into the traction system. Utilizing detailed track information to develop a traction system power demand schedule will allow further optimization of the power balance between the turboalternator and flywheel. Using this schedule, the energy storage level in the flywheel can be optimized to accommodate upcoming traction system demands.

The sections below provide additional information about the turboalternator package and flywheel energy storage system.

Turboalternator Package

The turboalternator provides the prime power for the locomotive with a speed-matched gas turbine and synchronous alternator. The turbine engine will run on diesel fuel #2, used currently throughout North America. At an operational speed of 12,000 to 15,400 rpm, the engine and generator are dramatically lighter and smaller than those used in slower speed systems. Fig. 2 shows the general arrangement of the turboalternator system components.

The generator includes a brushless exciter which requires a field supply of only 2 kW to control the power output of over 3 MW. The generator armature is wound in eight poles, so the three-phase power is generated at 800 to 1,027 Hz. The generator is actively cooled by an oil circulation system in the rotor, and a compressed air system in the stator and air gap. Together, these auxiliaries are expected to remove about 85 kW of heat when operating at full rated conditions. The auxiliaries were designed to keep the maximum generator temperature below 220°C, when operating in ambient conditions up to 50°C and an elevation to 1,500 m (5,000 ft) above sea level. Internal temperature sensors will be used to evaluate the effectiveness of the cooling system under operating conditions.

The oil cooling system includes a 480 V main pump motor and a dc-powered priming and backup pump motor. Temperature-compensated flow control valves provide 11.4 lpm (3 gpm) of flow to each of two bearing and seal circuits, and about 114 lpm (30 gpm) of flow to the rotor cooling circuit. The hydraulic fluid selected (MIL-L-23699E) is a common product with the oil required by the gas turbine. The oil/air heat exchanger will be mounted in the roof cowling, as illustrated in Fig. 2.

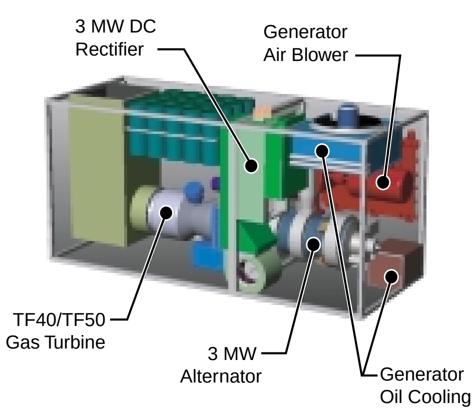

Fig. 2. Turboalternator system components

The air cooling system is required to supply about 2,000 scfm of flow at 3.8 psig to the generator. This flow is divided approximately in half before entering the inlet manifold at each end of the machine. The cooling path from both ends proceeds through the generator to the midsection into an exhaust manifold to be carried away. The exhaust air flow (up to 140°C) will be routed into the turbine exhaust flow before expulsion at the top rear of the locomotive. The size and mass of the air blower for this application were reduced by the use of a motor and 14,000 rpm speed-increasing gearbox (pictured in Fig. 2, far wall). Recent developments in high speed, directly coupled motors promise to further reduce the size and mass of this auxiliary before integration into the Bombardier locomotive is completed next year. Options to integrate this air stream with others in the turboalternator package are also being considered.

The power output of the generator is passively rectified before it is fed into the locomotive dc bus. Dual 52 mm fast-recovery diodes are employed in the six-position full bridge rectifier. An air-cooling system was selected to remove an expected 18 kW of conduction and switching losses from the diode assembly. This system requires 5,000 scfm of cooling air at a pressure drop of a few inches of water. For initial testing, a 7.5 hp blower provides this cooling air, but the final integration design will endeavor to leverage this air flow from the turboalternator cooling air streams. Physically, the ALPS turboalternator package is installed on a mounting platform similar to the Bombardier baseline High Speed Demonstration Locomotive package. The common mounting platform will facilitate the exchange of prime movers and power generation components for demonstration of the ALPS system in the Bombardier locomotive.

The high speed generator and its associated auxiliary systems are currently being tested at the UT-CEM laboratory under no-load conditions.

Flywheel Energy Storage System

The design of the flywheel energy storage system leverages experience developed at UT-CEM during demonstrations of high energy, high power pulsed power supplies. The ALPS flywheel energy storage system consists of a 480 MJ energy storage flywheel directly coupled to a 2 MW high speed motor/generator. The energy storage system also includes a high frequency power conversion module and auxiliary support systems. Table 2 summarizes the specifications of the ALPS flywheel energy storage system. Fig. 3 is a section view of the energy storage flywheel identifying the major components.

Table 2. Flywheel performance specifications

Parameter	Value
Operating speed range	7,500 rpm to 15,000 rpm
Stored energy at 15,000 rpm	480 MJ
Delivered energy 15,000 rpm to 7,500 rpm	350 MJ
Rated output power	2 MW
System estimated weight	8,600 kg
Envelope dimensions (diameter × overall length)	1.5 m × 2.8 m

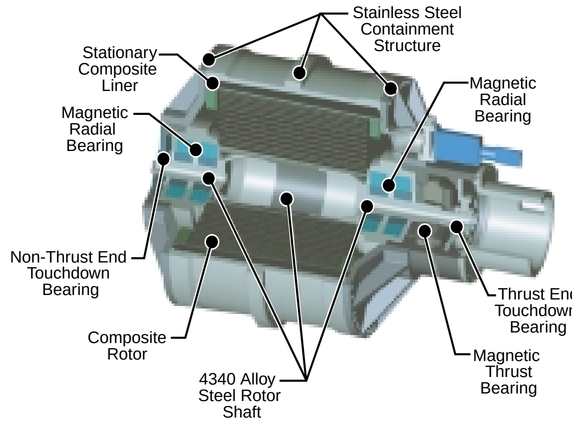

Fig. 3. Section view of energy storage flywheel

The flywheel composite rotor is supported on a three piece 4340 alloy steel shaft assembly, and is made up of a total of 14 concentric composite rings. The composite rings are filament wound structures using a variety of glass and graphite fibers pre-impregnated with an elevated temperature cure epoxy resin. The concentric rings are assembled with interference fits to manage radial stresses developed during spin.

The rotor is levitated on an active magnetic bearing system to minimize bearing drag losses and auxiliary requirements and to allow long term operation in a vacuum environment. Both the radial and axial magnetic bearings are permanent magnet bias type with active control coils mounted in the stators. This configuration minimizes eddy current losses on the rotating components of the bearing system and provides stable control in a locomotive dynamic environment. The touchdown bearings (needed when the rotor is not magnetically levitated) consist of conventional ceramic rolling element bearings mounted in squeeze film dampers.

The magnetic bearings and touchdown bearings are mounted in an enclosure consisting of two CF-8 stainless steel endplates and a 304 stainless steel forged housing. In addition to supporting the bearings, the containment structure provides a vacuum enclosure for the rotor cavity. Operation of the rotor in a vacuum is required to minimize the windage losses and frictional heating on the flywheel. The flywheel enclosure also supports a composite containment liner designed to safely contain the energy released in the unlikely event of a burst of the outer ring of the flywheel.

The flywheel rotor shaft is directly coupled to a high speed motor/generator through a custom designed flexible coupling which supports an integral high speed shaft seal. The Ferrofluid™ seal allows 15,000 rpm operation at an enclosure vacuum of 10^{-3} torr with minimal frictional losses.

Two options for the flywheel motor/generator are being considered. The first option is a 3 MW high speed generator essentially identical to the generator in the turboalternator package. The second high speed synchronous generator would require slight modifications to allow operation in the vertical orientation required for the flywheel motor/generator application. The second option for the flywheel motor/generator and high frequency power converter are variants of an existing high performance traction system developed by United Defense for a military vehicle application. The United Defense traction system components must be modified to match the dc bus voltage of the Bombardier demonstration locomotive and would also need to be capable of operation in a vertical orientation. The United Defense high frequency power converter could also be used in conjunction with the Honeywell International synchronous generator.

Performance Simulations

The ALPS propulsion system components have been designed to meet minimum locomotive performance specifications established by FRA for the High Speed Non-Electric Locomotive Demonstration Program. In phase I of the program, a consist of one locomotive and four Amfleet Type II cars must achieve 125 mph in 5 min at sea level and 105ºF ambient temperature. For operation with the flywheel in phase II of the program, an identical consist must achieve 150 mph in 4 min under the same conditions. In order to evaluate the propulsion system performance required to meet these goals, extensive computer modeling was conducted at the Association of American Railroads Transportation Technology Center, Inc (AAR/TTCI). Table 3 lists the routes and speeds used in the TEM simulations. The north end of the Northeast Corridor from New York to Boston was used in the simulation in order to compare the performance of the ALPS system relative to electric locomotives.

Using a train energy model (TEM) developed at AAR/TTCI, different combinations of prime power and flywheel energy storage were simulated to establish the minimum performance requirements for both 125 mph and 150 mph operation. The simulations also evaluated the trip time and fuel consumption characteristics of the baseline 1-4-0 configuration as well as 1-8-1 consists. The TEM simulations use track charts from existing routes as an input to allow an accurate evaluation of the benefits of the ALPS propulsion system on actual routes.

Comparing the turbine only system to the ALPS concept shows the benefits that the flywheel provides to the overall system performance. The simulation results shown in Table 4 for the north end of the Northeast corridor provide an example.

The boost power provided by the flywheel results in at least a 5 min trip time reduction for a 1-8-1 consist. In cases where unexpected stops or speed reductions are experienced, the boost power helps in making up lost time. The fuel savings come primarily from the recovery of braking energy and by operating the turbine at peak efficiency for more of the time. Additional operating cost savings and improved reliability are realized by increasing the gas turbine overhaul interval. The cost of the improved locomotive performance is the added weight of the flywheel, which increases the weight of the locomotive by approximately 5%. Careful locomotive integration design should be able to accommodate the increased propulsion system size and weight.

It is also possible to use an ALPS equipped locomotive in a 1-8 configuration for lower speed (90 to 110 mph) service. This configuration provides the same acceleration performance as a conventional 1-8-1 diesel locomotive consist. ALPS technology can therefore be effective before corridor speed limits are increased, and is able to grow with the needs of emerging high speed corridors.

Table 3. Routes simulated using TEM model

Route	Route Length and Speed Limits
New York to Boston*	231 miles (110 and 150 mph)
New York to Albany, NY	143 miles (110 and 125 mph)
New York to Washington	225 miles (125 and 150 mph)
Portland to Seattle	186 miles (75 and 125 mph)
Raleigh to Charlotte	170 miles (100 and 125 mph)
Fredericksburg to Washington	59 miles (70 mph)
Chicago to St. Louis	282 miles (110 mph and 125 mph)

Table 4. ALPS performance comparison

Parameter	TF40 Turbine Engine with Conventional Alternators	TF40 Turbine Engine with Flywheel	Comments
Peak Propulsion Power	4,000 hp	7,000 - 8,000 hp	Boost power improves acceleration
Fuel Consumption*	1,113 gallons	1,024 gallons	8% reduction
Trip Time*	2 hrs, 53 min	2 hrs, 48 min	At least a 5 minute savings
Turbine Thermal Cycles*	103	37	Reduces maintenance costs
Propulsion System Volume	120 ft^3	214 ft^3	Includes auxiliary systems
Propulsion System Weight	11,540 lbs	24,100 lbs	5% increase in locomotive weight

* New York to Boston simulations used for comparison only

Fig. 4. High speed generator components during final assembly (engineer S. Pish pictured)

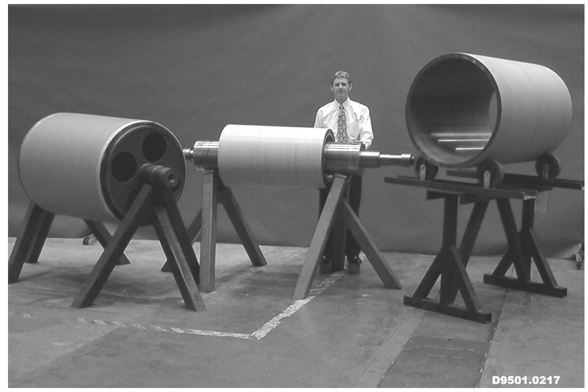

Fig. 5. Flywheel components during final assembly (engineer B. Sledge pictured)

Current Status

Fabrication and assembly of the ALPS components is nearing completion and verification testing will begin soon. The ALPS testing is progressing toward the rolling demonstration of a fully configured turboalternator and flywheel driven locomotive consist. Final assembly of the high speed generator was completed in April 2000 and no-load testing is currently in progress at the UT-CEM facility in Austin, Texas. This phase evaluates the generator design and fabrication, measuring the full range of voltage and current generation and the various loss mechanisms of windage, conduction, and eddy currents. Fig. 4 shows the high speed generator components during final assembly.

Once no-load testing is completed, the high speed generator will be moved to the Naval Business Center in Philadelphia where it will be mated with a TF40 gas turbine for full load tests of the turboalternator system. These tests will bring the generator to full power load, using a 3.5 MW resistive load bank constructed by AAR/TTCI. After load testing is complete, the turbine and high speed generator will be assembled into the package for integration into the Bombardier demonstration locomotive.

Fabrication of the composite rings for the flywheel is in progress and assembly of the completed rings is proceeding in parallel. Laboratory testing of the flywheel at the UT-CEM facility will begin during the last quarter of calendar year 2000. Fig. 5 shows the flywheel components during final assembly.

After the laboratory testing, the flywheel will be integrated into a tender car in preparation for the initial demonstrations with the Bombardier locomotive.

Conclusions

Development of high speed non-electric passenger locomotives is key to the cost effective expansion of high speed rail on corridors throughout the United States. The ALPS system provides a path to high speed passenger rail operation on existing infrastructure with performance comparable to existing electric locomotives while avoiding or deferring the cost of electrification. The advanced propulsion system provides excellent acceleration performance and addresses the two major concerns associated with gas turbines in locomotives by positively influencing fuel economy and turbine maintenance intervals.

Acknowledgment

This work has been sponsored by the Federal Railroad Administration. Support for the project has also been provided by the State of Texas, the Defense Advanced Research Projects Agency (DARPA), the Southern Coalition for Advanced Transportation (SCAT), the New York State Department of Transportation, the U.S. Navy, and Honeywell International.

Contact Information

John Herbst
ALPS Project Manager
The University of Texas at Austin
Center for Electromechanics
J.J. Pickle Research Campus, Mail Code R7000
Austin, TX 78712
(512) 232-1645
j.herbst@mail.utexas.edu